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Scalability of Robotic Controllers: Effects of Progressive Levels of Autonomy on Robotic Reconnaissance Tasks

by Rodger A. Pettitt, Elizabeth S. Redden, Estrellina Pacis, and Christian B. Carstens

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NOTICES

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14. ABSTRACT

This investigation of the effects of progressive levels of autonomy on robotic reconnaissance task performance was a cooperative effort between the U.S. Army Research Laboratory/Human Research and Engineering Directorate (ARL/HRED) and Space and Naval Warfare Systems Center San Diego (SSC Pacific). Thirty Soldiers served as participants. After training on the operation of the robotic system, each Soldier completed building reconnaissance exercises using three different levels of robotic automation (teleoperation, semi-autonomous, and autonomous operation). The participants' primary tasks were to map the floor plan of the building, and to identify and photograph objects of interest (situational awareness tasks). In order to increase the cognitive demand, Soldiers responded to requests for information while operating the robot. Dependent variables included objective performance data, data collector observations, and Soldier questionnaires. Reconnaissance times were significantly faster and there were significantly fewer driving errors when the robot was in the autonomous mode than when it was in the other two modes. Performance in the semi-autonomous mode was significantly better than in the teleoperation mode. As the level of autonomy increased, workload, reconnaissance times, and driving errors decreased and mapping accuracy increased. There were no significant differences among the conditions in situational awareness or target identification.

15. SUBJECT TERMS

robot control, autonomous, teleoperation, semi-autonomous

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Contents

List of Figures

List of Tables

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1. Introduction

1.1 Background

Maes (1995) proposed a continuum of robot control that ranges from teleoperation to full autonomy. Robots can be placed on this continuum based on the level of human-robot interaction that is required. Teleoperation is the lowest level of automation on the continuum because it requires the most intervention from the robot operator. A teleoperated robot is totally under the control of the operator who uses a joystick or other control device to command the robot. This requires constant interaction between the robot and the operator. Teleoperation is not the ideal solution for all situations. Many teleoperation tasks are repetitive and boring and the work requires constant attention by the operator.

Semi-autonomous control (often called supervisory control) requires the operator to provide an instruction or portion of a task that can safely be performed by the robot on its own. Two types of semi-autonomous control are often identified—shared control (also called continuous assistance) and control trading. Shared control requires the teleoperator to delegate a task for the robot or to accomplish it via direct control of the robot. If the operator delegates control to the robot, he or she must still monitor the robot to ensure that it is performing the task correctly. A guarded teleoperated robot can be placed on this portion of the continuum because it has the ability to sense and avoid obstacles but will otherwise navigate as driven, like a robot under manual teleoperation. During control trading, the human only interacts with the robot to give it a new command or to interrupt it and change its orders. A line-following robot can be placed on this portion of the continuum if it simply follows something painted, embedded or placed on the floor and does not have the ability to circumnavigate obstacles on its own.

After receiving instructions, autonomous robots (those that perform tasks independently and/or have the capacity to choose goals for themselves) operate under all reasonable conditions without recourse to an outside operator and can handle unpredictable events (Haselager, 2005). Huang, et al. (2005) state that a fully autonomous robot has the ability to gain information about the environment, work for an extended period without human intervention, move itself through its environment without human assistance, and avoid situations that are harmful to people, property, or itself unless those are part of its design specifications. An autonomously guided robot can be placed on this portion of the continuum because it knows at least some information about where it is and how to reach waypoints (Murphy, 2000). Knowledge of its current location is determined by using sensors such as lasers and global positioning systems (GPS). Positioning systems determine the location and orientation of the platform, so the robots can plan a path to their next waypoints or goals. Autonomous robots make their own choices instead of following goals set by other agents. A robot that is capable of goal generation can also be placed on this portion of the continuum.

The incorporation of autonomous robotic systems into military schema involves more than just effective system design. It is also important for designers to understand which potential robotic system autonomous capabilities match or surpass human abilities and when, during scenario accomplishment, the human needs assistance or is overloaded. This knowledge is needed in order to leverage autonomous robotic behaviors for optimal performance. Thus the goal is to optimize the human and robot roles in a task. To do this, robot control competencies and inefficiencies must first be identified and then they must be understood in relation to specific task performance. Trade-offs among levels of autonomy must be identified. For example, an autonomous system may have a slower reaction time to difficult problems than a system being teleoperated by a human but latency involved in teleoperation could render the human's reaction time ineffective. Also, moderators of robot control performance must be identified. For example, workload is also an important moderator of human task performance. The effectiveness of a control system is likely to depend a great deal on situational task demands. The requirement for the operator to perform simultaneous tasks such as controlling multiple robots or performing local security tasks could have a detrimental effect on human intervention in robotic task outcomes because of human availability at a certain point in time and because of cognitive overload.

Many studies have demonstrated that operators' situation awareness (SA) was higher when they were controlling robots with semiautonomous or autonomous capabilities (Chen et al., 2008; Dixon et al., 2003; Luck et al., 2006). However, increased autonomy is not a panacea. In a two-year study of a collaborative human-robot system Stubbs et al. (2007) found that as autonomy increased, users' inability to understand the reasons for the robot's actions disrupted the creation of common ground. Also, many fear that providing more and more autonomy to armed robots could result in collateral damage or fratricide (Singer, 2009).

1.2 Objective

The goal of this research was to examine the effectiveness of different levels of automation (teleoperation, semi-autonomous, and autonomous) on robot control in reconnaissance missions when the robotic operator is fully engaged in additional high cognitive load activities. Our hypothesis was that full autonomy would be the most effective level of autonomy for a robotic reconnaissance mission when the robotic operator is fully engaged in a high cognitive load activity.

1.3 Overview of the Experiment

This study was a cooperative research effort between the U.S. Army Research Laboratory (ARL)/Human Research and Engineering Directorate (HRED) and the Space and Naval Warfare Systems Center San Diego (SSC Pacific). It was an investigation of the effect of progressive levels of automation on robotic reconnaissance task performance. It took place at Fort Benning, GA. Thirty Soldiers from the Officer Candidate School (OCS) and the Warrior Training Center (WTC) participated in the study. After training on the operation of the robotic system, each

Soldier completed reconnaissance exercises using three different levels of robotic automation (teleoperated, semi-autonomous and autonomous). During the exercises, Soldiers responded to requests for information regarding situation and mission awareness. The terrain and hazards were counter-balanced along with the automation level to control for the effect of learning. Automation level and usability were evaluated based on objective performance data, data collector observations, and Soldier questionnaires.

2. Method

2.1 Participants

Thirty Soldiers from the OCS and WTC participated in the study. The OCS participants included Soldiers with prior enlisted service with a variety of backgrounds and experience levels as well as those just coming into the Army from college. The WTC Soldiers consisted of enlisted Soldiers with the rank of E-4 through E-6 serving as instructors for the pre-Ranger and air assault courses.

2.1.1 Pretest Orientation

The Soldiers were given an orientation on the purpose of the study and what their participation would involve. They were briefed on the objectives and procedures, as well as on the robot. They were also told how the results would be used and the benefits the military could expect from this investigation. Any questions the subjects had regarding the study were answered.

2.2 Apparatus and Instruments

2.2.1 SSC Pacific Robot

The SSC Pacific robot (figure 1) is an iRobot PackBot Scout, equipped with a 1st generation Navigator payload. The payload contains a sensor suite that includes an inertial measurement unit (IMU), a gyroscope, a compass, GPS, and a 360° ladar. The IMU, gyroscope, compass, and GPS are used for positioning, localization, and navigation, while the ladar is used for obstacle avoidance and mapping. In addition, the payload contains a processor that runs the Autonomous Capability Suite (ACS) that includes all the autonomous behaviors onboard the robot and Freewave radio to communicate with the operator control unit. The scalability and configurable framework of ACS provided the key sliding autonomy feature needed to conduct this experiment; the operator was able to change the level of autonomy onboard the robot by a press of a button on the operator interface.

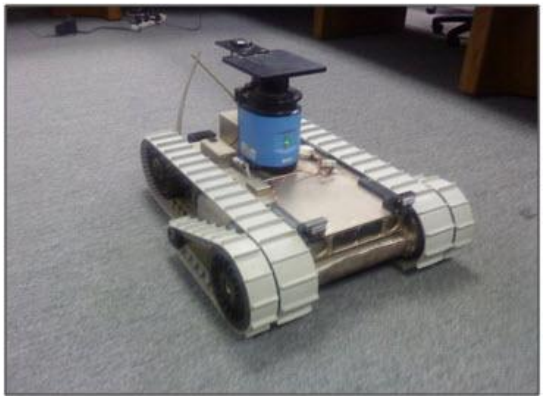

Figure 1. SSC Pacific robot with 1^{st} generation navigator payload.

2.2.2 Operator Interface

The operator interface used to control the system was based on SSC Pacific's Multi-Robot Operator Control Unit (MOCU). An example screenshot of the interface is found in figure 2. The robot's location, driven path, goal points, and sensor data (i.e., map data) were overlaid on an aerial image. Real-time video from the robot was also displayed.

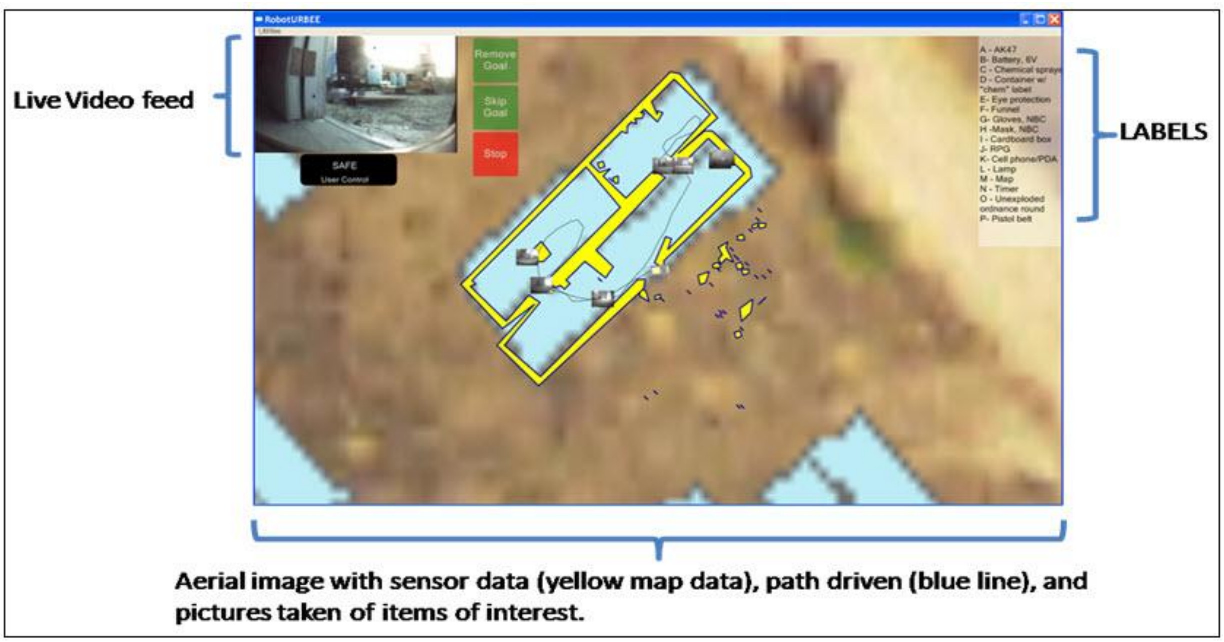

Figure 2. Snapshot of MOCU interface.

Various button and joystick controls were also provided to send drive commands to the robot, as well as to turn on and off the robot's behaviors. This allowed the operator to control the sliding autonomy available on the robot. Three levels of autonomy were achieved by turning on and off

robot behaviors. All behaviors were turned off during teleoperation so that the operator was in complete control of all robot actions and the operator had to draw the building map and mark the location of items of interest by hand. Semi-autonomy was achieved by using the obstacle avoidance, mapping, and return-to-start functions available on the robot. This function assisted the robot operator during driving by automatically avoiding obstacles, self directing itself to open spaces, building a map of the building for the operator, and returning to the start location on its own when the operator completed his/her mission. Full autonomy was achieved by turning on the efficient exploration behavior in addition to all the behaviors included under semi-autonomy. Table 1 shows the behaviors used for each level of autonomy.

Table 1. Autonomous behaviors used for each level of autonomy.

	Self-Directing	Obstacle Avoidance	Mapping	Return-to-Start	Exploration
Teleoperated	No	No	No	No	No
Semi-autonomous	Yes	Yes	Yes	Yes	No
Fully-autonomous	Yes	Yes	Yes	Yes	Yes

The MOCU software was developed independent of the hardware unit, and thus can be run on any computer. A commercial grade off-the-shelf (COTS) laptop was used in the experiment to run MOCU. A Microsoft Xbox 360 wireless (figure 3) controller was used to provide a joystick/button interface.

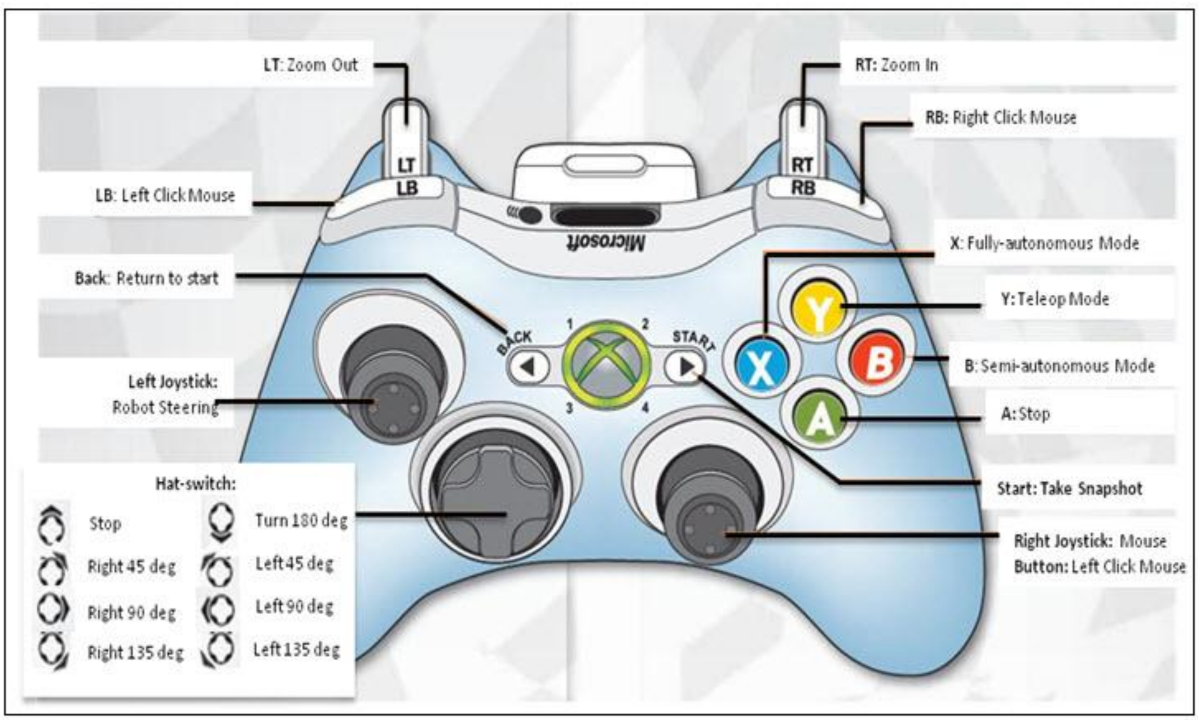

Figure 3. Microsoft Xbox 360 wireless controller.

2.2.3 Building Reconnaissance Course

The building reconnaissance course (figure 4) was located at Molnar military operations in urban terrain (MOUT) site, Ft Benning, GA. It consisted of three one-story buildings that were similar in size but with different floor plans. Soldier operators were located out of the line of sight of the robot in a stationary position inside a separate building.

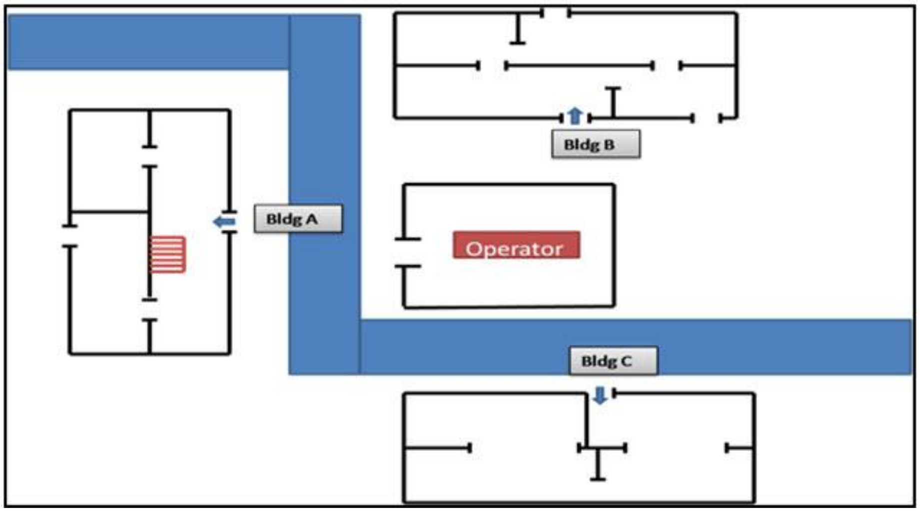

Figure 4. Building reconnaissance course.

Various items were placed in the rooms of each building and arranged to represent a specific enemy activity. Building A was configured to represent a chemical weapons factory, building B was configured to represent a staging area for a terrorist attack against the United States, and building C was configured to represent a prisoner of war (POW) interrogation facility. Figures 5–7 show the floor plans and placement of items for each building.

Item	Description
1	AK47
2	AK47
3	AK47
4	RPG
5	Cardboard box
6	6v Battery
7	NBC Mask
8	NBC Gloves
9	Eye Protection
10	120 mm Tank Round
11	120 mm Tank Round
12	120 mm Tank Round
13	105 mm Arty Round
14	105 mm Arty Round
15	Funnel
16	Chemical Sprayer
17	Container with Chemical warning label
18	Container with Chemical warning label
19	Cell Phone

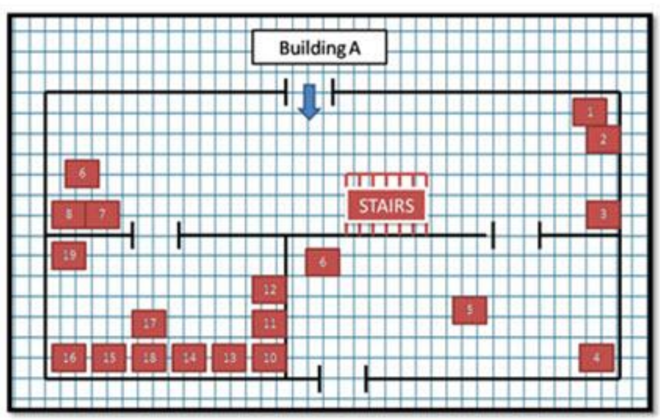

Figure 5. Building A: chemical weapons factory.

Item	Description
1	Diet Pepsi Caffeine Free Can bomb
2	Diet Coke bomb
3	Diet Pepsi Can bomb
4	Land Mine Grey
5	Land Mine Green and Tan
6	Land Mine Tan
7	Cardboard box
8	picture of statue of liberty
9	Suicide bomber vests
10	Suicide bomber vests
11	Suicide bomber vests
12	Briefcase bomb
13	Map with New York circled
14	Timer
15	6v Battery
16	Wire
17	Initiation Device
18	PDA
19	Cell Phone
20	Pipe Bomb
21	82mm Mortar round
22	122mm Projectile
23	130mm Rocket round

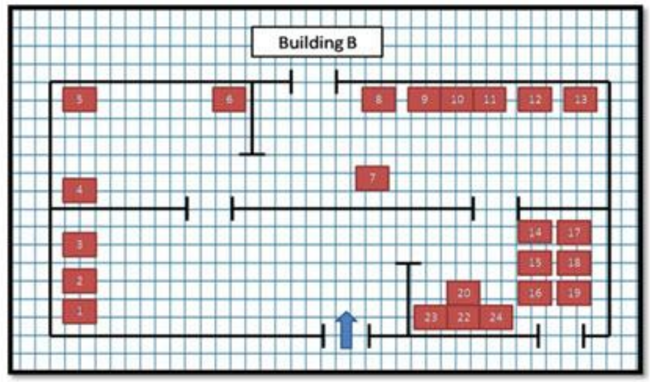

Figure 6. Building B: terrorist staging area.

Item	Description
1	Cardboard box
2	PDA
3	Fan
4	AK 47
5	AK47
6	AK47
7	RPG
8	12v Battery
9	Jumper cables
10	Chair
11	Table
12	Lamp
13	Wire
14	Rope
15	Wire
16,17	ACU uniform
18	Bedding
19	Bloody rags
20	Tortured dead body
21	Sandbag over head
22	Chair
23	Bedding

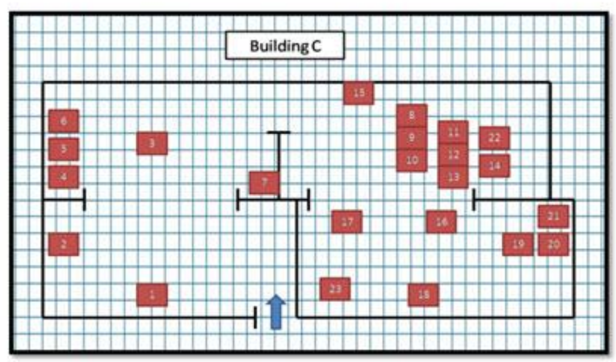

Figure 7. Building C: POW interrogation facility.

2.2.4 The National Aeronautics and Space Administration-Task Load Index (NASA-TLX)

The NASA-TLX is a subjective workload assessment tool that allows subjective workload assessments on operators working with various human-machine systems (Hart and Staveland, 1988). It uses a multi-dimensional rating procedure that derives an overall workload score based on a weighted average of ratings on six subscales. These subscales include mental demands, physical demands, temporal demands, own performance, effort, and frustration. It can be used to assess workload in various human-machine environments such as aircraft cockpits; command,

control, and communication workstations; supervisory and process control environments; simulations; and laboratory tests. The version of the NASA-TLX used during this experiment was presented to the Soldiers on a computer. Definitions of each scale were provided on laminated paper so the participates could refer to it as they were providing their estimates of the workload associated with each type of small unmanned ground vehicle (SUGV) control on the various scales.

2.2.5 Questionnaires

A demographic questionnaire was administered to gather information concerning demographic data, robotic experience, and physical characteristics that might have had an effect on the participant's ability to operate the robot. The questionnaires given after participation in the events were designed to elicit Soldiers' opinions about their performance and experiences with each of the control systems. They asked the Soldiers to rate the devices on a 7-point semantic differential scale ranging from "extremely good/easy" to "extremely bad/difficult." A post iteration questionnaire was administered to each Soldier at the end of each iteration with each level of autonomy, and an end of experiment questionnaire was administered at the completion of all three iterations.

2.3 Procedures

2.3.1 Soldier Orientation

Upon arrival, the experiment Soldiers received a roster number, which was used to identify them throughout the evaluation. During the pretest orientation, the Soldiers were given an operations order that explained the robotic mission that they would be undertaking during the experiment. A copy of the operations order can be found in appendix A (FM 5-170, 1998). It was explained to them that upon completion of training they would complete three iterations of the building reconnaissance course (one with each level of autonomy) according to the matrix in table 2. All instruments that were used, the training course, and the building reconnaissance course were explained and any questions the Soldiers had concerning the experiment were answered. They were also told how the results would be used and the benefits the military could expect from the investigation. Demographic data, as well as data concerning their Army and robotic experience and physical characteristics, were also taken for each Soldier.

Table 2. Order of treatments and lanes.

	Building and Iteration		
Roster Number	**Bldg A, Trial 1**	**Bldg B, Trial 2**	**Bldg C, Trial 3**
1, 16	T	S	A
2,17	A	T	S
3,18	S	A	T
4,19	T	A	S
5,20	S	T	A
6,21	A	S	T
7,22	S	T	A
8,23	A	S	T
9,24	T	A	S
10,25	S	A	T
11,26	T	S	A
12,27	A	T	S
13,28	S	A	T
14,29	A	T	S
15,30	T	S	A

Note: T = teleoperation; S = semi-autonomous; A = autonomous

2.3.2 Demographics

Demographic data were taken for each Soldier. Data concerning their physical characteristics and experience, especially their knowledge of operating remote controlled vehicles, were included in the demographic data sheet. The demographic data sheet is shown in appendix B.

2.3.3 Training

Training was conducted by a representative of SSC Pacific. Groups of three Soldiers were given an overview of the robot capabilities, controls, and sensors, and the three autonomy levels were explained. Then each Soldier was given 15 min of individual hands-on training that included practice on the tasks required to perform the building reconnaissance in all three levels of autonomy. The trainer assessed whether the Soldiers were capable of performing the tasks in all three levels of autonomy before they were allowed to participate in the study.

During training, Soldiers were issued a battalion level operations order outlining the reconnaissance mission they were supporting. Each Soldier was given about 15 min to read the order prior to conducting the reconnaissance course.

2.3.4 Building Reconnaissance Course

The Soldiers completed the building reconnaissance course with the level of autonomy and the lane order assigned in table 2. The course consisted of three different one-story buildings so the Soldiers could reconnoiter a different building with each level of autonomy.

During teleoperation trials, the robot was manually driven using the video feed displayed on the MOCU interface and left joystick gimbal on the Microsoft Xbox 360 wireless controller (figure 3).

During the semi-autonomous trials, the robot's obstacle avoidance, mapping, and return-to-start behaviors were turned on, and the robot self-directed itself through the building to the next open space available. The Soldier was able to stop the robot from self-directing itself and take control at any time by pressing the A button to stop the robot and used the left joystick gimbal to influence the robot's direction. To turn on the robot's self-directing behavior again, the Soldier pressed the B button. The obstacle avoidance feature was always on to prevent the robot from running into objects. To turn obstacle avoidance off, the Soldier had to switch to teleoperation mode by pressing the Y button. When the Soldier decided all items of interest were found, the BACK button was pressed on the X-box controller and the robot returned to the starting location on its own.

During the fully-autonomous trials, the robot's obstacle avoidance, mapping, and return-to-start behaviors were turned on, as well as an efficient exploration behavior that helped the robot self direct itself in places it had not driven to yet, to minimize the overall time to explore the building while maximizing coverage area. As in the semi-autonomous mode, the Soldier was able to stop the robot at any time by pressing the A button. The Soldier could also switch teleoperation mode (by pressing the A button) or semi-autonomous mode (by pressing the X button). Also as in the semi-autonomous mode, the Soldier was able to send the robot back to the starting location by pressing the BACK button.

For all three trials in each of the autonomy levels, the Soldier was required to take snapshots of items of interest found and label them. The camera was in a fixed position facing the front of the robot and did not have a pan and tilt capability. In order to take a snapshot, the Soldier had to maneuver the robot into a position facing the item. To label the snapshots, the Soldier used the right joystick gimbal to move the mouse to the snapshot, click the right trigger button on the X-box controller to bring up the list of labels, and then click the left trigger button to select the label.

Soldiers were instructed that their primary tasks were to provide a map of the floor plan of the building, to identify objects of interest (SA task) and take a snapshot of them, and return the robot to the starting point as quickly as possible once the entire building had been reconnoitered and mapped. During autonomous and semi-autonomous trials, the system automatically mapped the buildings as the robot maneuvered through them and snapshots of the items appeared on the map in the location they were taken. During teleoperated trials, Soldiers were instructed to draw a scaled map by hand of the floor plan of each building depicting the location of items of interest.

The Soldiers' secondary tasks were to answer questions concerning details of their mission based on the information provided in the operations order, and to identify different types of smoke grenades. The secondary tasks served as an additional cognitive load. Secondary task questions were asked at 2 min intervals throughout the reconnaissance. Mission details could be found in excerpts of the operations order that was provided to them during each trial. They were instructed to look up and answer questions about the operations order only if doing so did not interfere with performance of the primary tasks.

A data collector accompanied the robot to record completion times and driving errors (i.e., running into walls or objects with the robot). Another data collector was present at the operator station to record the number and types of items of interest identified (SA task), and to ensure the Soldiers prioritized their focus on the primary task. An additional data collector asked the Soldiers secondary task questions at two minute intervals and recorded their responses.

Upon the completion of the iteration, the Soldiers were provided with a list of the items of interest they identified and were asked to answer situational awareness questions concerning the type of enemy activity that had taken place in the building based on the items found in the building. They were also asked to fill out questionnaires concerning the trial they just completed and to fill out a NASA-TLX concerning the level of workload experienced.

2.3.5 End of Iteration Questionnaire Administration

Questionnaires, designed to assess participants' performance and experiences with each level of autonomy, and the NASA-TLX were administered to each Soldier at the end of each iteration. After completing the course with each level of autonomy, the Soldiers completed an end of experiment questionnaire that compared each condition.

2.4 Experimental Design

The design of this experiment was a single factor repeated measures design (table 2).

2.4.1 Independent variable

- Level of autonomy (reconnaissance course events).

2.4.2 Dependent Variables

- Building reconnaissance course completion time.
- The number of driving errors on each course.
- The number of correct objects of interest found on each course.
- Accuracy of maps created during the building reconnaissance course (correct number of doors, items of interest in correct relation to each other, correct number of rooms).
- SA questionnaire responses.

- Number of secondary task questions answered correctly.
- NASA-TLX scores for each level of automation after each course is completed.
- Data collector comments.
- Questionnaire ratings and comments.

2.5 Data Analysis

All objective data collected on the reconnaissance courses were analyzed using repeated measures analysis of variance (ANOVA). Follow-on pair wise comparisons were done using Holm's Bonferroni procedure to control for family-wise error rates (Holm, 1979). Partial eta squared (η^2_p), an index of effect size, was computed for each ANOVA. Iteration effects were controlled through the counterbalanced order of the experimental design (table 2). Soldier questionnaire data were analyzed using descriptive statistics on the subjective ratings.

3. Results

3.1 Demographics

The Soldiers ranged in rank from E4 to E6. The average age of the Soldiers was 28 years and the average time in service was 68 months. None of the Soldiers had any prior experience in teleoperating a ground unmanned robot. Detailed responses to the demographics questionnaire are available in appendix B.

3.2 Training

The participants rated the training as being very good for all levels of autonomy. They indicated that the hardest task to learn was mapping the building in the teleoperation mode. Driving the robot was the easiest task to learn in all three levels of autonomy. Detailed responses to the training questionnaire are available in appendix C.

3.3 Building Reconnaissance Course Results

3.3.1 Robotic Control Results

Table 3 and figure 8 show the mean times to complete the course using each of the operation modalities. A repeated measures ANOVA showed that there was a significant difference among the means, $F(2,58) = 17.4$, $p<0.001$, $\eta^2_p = 0.383$. Follow-on paired-sample *t*-test comparisons were conducted using Holm's sequential Bonferroni correction for family-wise error rate. As shown in table 4, the average course completion time in the teleoperation condition was significantly slower than average times for the semi-autonomous and autonomous conditions. The slower times demonstrated during the teleoperation trials can be attributed to the requirement to manually map the buildings as well as an increased driving error rate. The

average course completion times in the semi-autonomous and autonomous conditions approached significance (p = 0.069) with the semi-autonomous condition being slower than the autonomous condition.

Table 3. Mean course completion times (min:sec).

Condition	Mean	SD
Teleoperation	16:01	3:54
Semi-autonomous	12:40	4:06
Autonomous	11:21	3:09

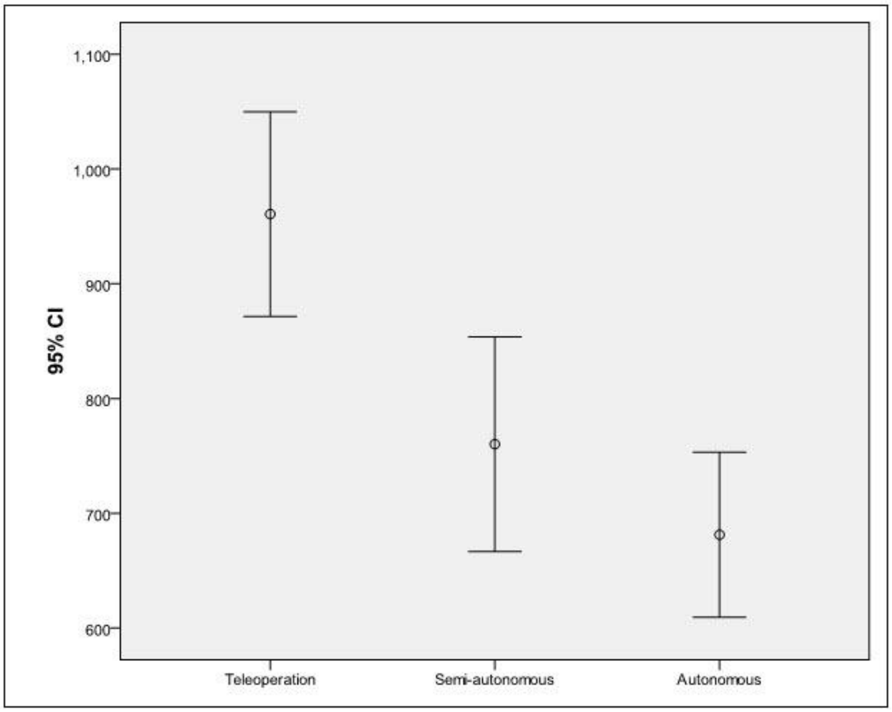

Figure 8. Mean course completion times (s) with 95% confidence intervals.

Table 4. Follow-on paired comparisons, course completion times.

Pair	*t*	*df*	Obtained *p*	Required *p*
Tele vs. Semi	3.77	28	0.001[a]	0.025
Tele vs. Auto	5.75	29	<0.001[a]	0.0167
Semi vs. Auto	1.89	28	0.069	0.05

[a] p<0.05, 2-tailed

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Table 5 and figure 9 show the mean number of driving errors with the three operation modalities. A repeated measures ANOVA indicated that there was a significant difference among the means, $F(2,58) = 7.24$, $p = 0.002$, $\eta^2_p = 0.200$. Follow-on paired comparisons, summarized below in table 6, indicated that there were significantly more driving errors in the teleoperation condition than in the semi-autonomous and autonomous control conditions.

Table 5. Mean driving errors.

Condition	Mean	SD
Teleoperation	3.67	3.33
Semi-autonomous	1.33	2.25
Autonomous	1.90	2.32

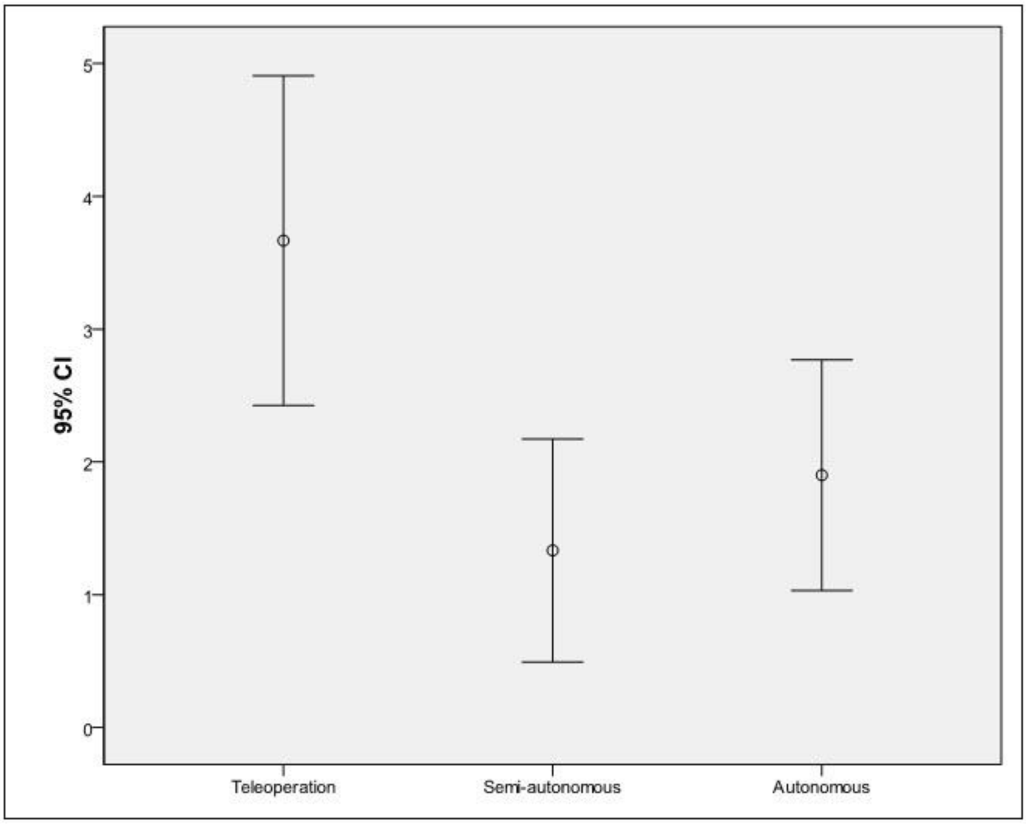

Figure 9. Mean driving errors with 95% confidence intervals.

Table 6. Follow-on paired comparisons, driving errors.

Pair	*t*	*df*	obtained *p*	required *p*
Tele vs. Semi	4.14	29	<0.001[a]	0.0167
Tele vs. Auto	2.52	29	0.017[a]	0.025
Semi vs. Auto	–0.88	29	0.388	0.05

[a] $p<0.05$, 2-tailed

Based on the post iteration questionnaire results, Soldiers rated the task of mapping the building during teleoperation trials as the most difficult task of the reconnaissance. In the autonomous and semi-autonomous conditions, an accurate map of the building was drawn on the display as the robot moved through the building. In the teleoperation condition the participants were given lined graph paper and asked to draw a diagram of the building, complete with doors and items found in the building. Because the quality of some of the drawings was so poor, it was difficult to interpret the drawings. We conducted a reliability check by having two independent raters code a random sample of fifteen diagrams for the number of doors, the number of doors in the correct location, and the total area (ft^2) of the building. The reliability coefficients are shown in table 7. Although all three correlation coefficients were statistically significant, there was substantial disagreement between the two raters in regard to the number and location of doors in the diagrams.

Table 7. Inter-rater reliabilities, teleoperation maps.

Measure	***r***	***p***
No. doors	0.65	0.009
No. doors correct wall	0.74	0.002
Area	0.92	0.000

The summary statistics from the map drawing ratings are shown in table 8. Although a few participants correctly identified all of the doors in the correct location, on average only about 2/3 of the doors were correctly identified and drawn in the correct location. All of the participants underestimated the area of the building, most by a substantial amount. One-sample *t*-tests were used to compare each mean against a value of 100% that would be obtained using the maps automatically generated in the semi-autonomous and autonomous driving conditions. Each of the means was significantly lower than 100%.

Table 8. Summary statistics, teleoperation maps.

Measure	**Mean**	**SD**	***t***	***df***	***p***
% doors identified	70%	25%	4.75	14	<0.001
% correct door location	67%	27%	4.70	14	<0.001
Area	40%	20%	11.83	14	<0.001

3.3.2 Situation Awareness Results

Table 9 shows the proportion of items detected (perception) in the three buildings for each robotic control condition. A repeated measure ANOVA indicated that there was no significant difference among the means, $F<1.00$.

Table 9. Mean proportion of items detected.

Condition	Mean	SD
Teleoperation	74%	14%
Semi-autonomous	75%	16%
Autonomous	72%	11%

3.3.3 Secondary Task Results

During the building reconnaissance trials, the participants were periodically asked questions regarding details contained in the operation order, or they were asked to identify specific types of grenades. Soldiers stated that performing the secondary task during the teleoperation trials was difficult because they had to concentrate more of their attention on driving and manual mapping tasks. Table 10 and figure 10 show the proportion of correct responses to these secondary task questions. A repeated measures ANOVA showed that there was a significant difference among the means, $F(2,58) = 3.79$, $p = 0.028$, $\eta^2_p = 0.115$. Follow-on paired comparisons, shown in table 11, indicate that secondary task performance was significantly better in the autonomous condition relative to the teleoperation condition.

Table 10. Mean % correct secondary activity.

Condition	Mean	SD
Teleoperation	41%	17%
Semi-autonomous	49%	25%
Autonomous	55%	25%

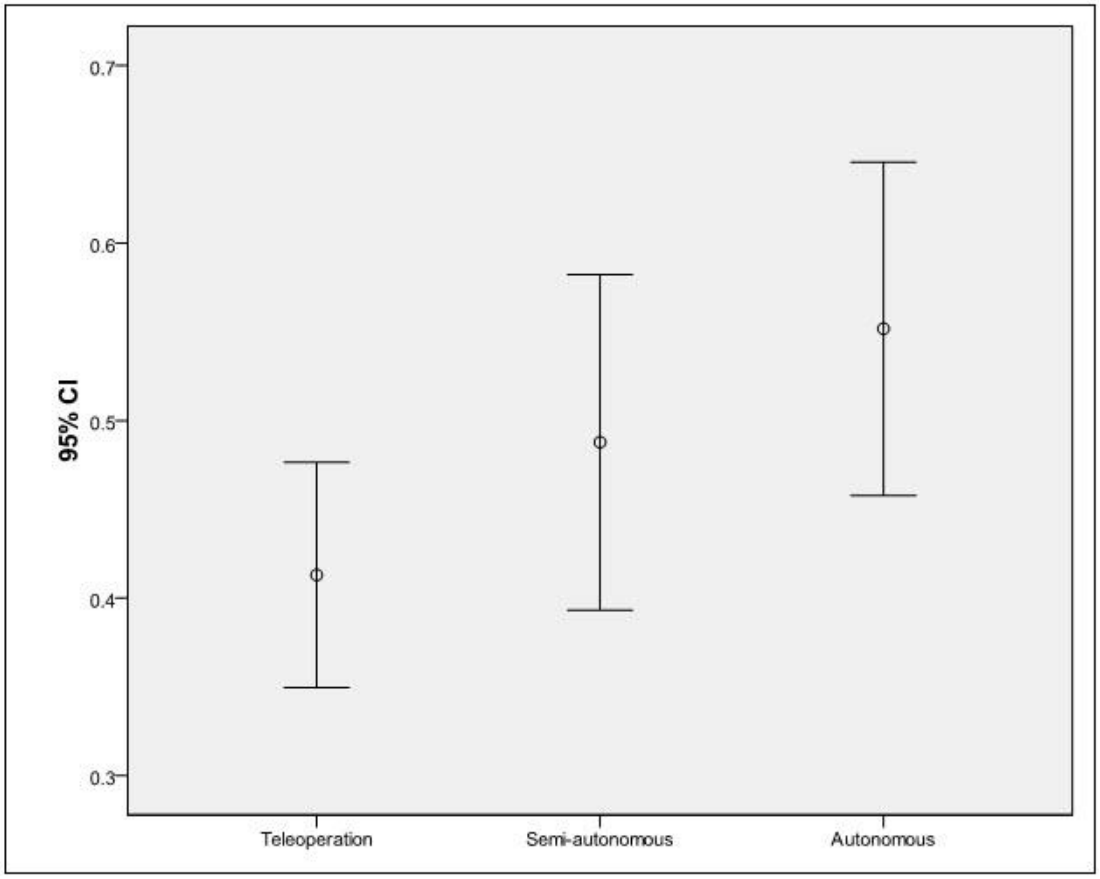

Figure 10. Mean % correct secondary task with 95% confidence intervals

Table 11. Follow-on paired comparisons, secondary task.

Pair	***t***	**df**	**Obtained *p***	**Required *p***
Tele vs. Semi	–1.51	29	0.143	0.025
Tele vs. Auto	–2.78	29	0.009[a]	0.0167
Semi vs. Auto	–1.23	29	0.227	0.05

[a]p <0.05, 2-tailed

3.4 NASA-TLX Results

Table 12 shows the weighted means on the NASA-TLX scales and the total workload means. The means for the three conditions are illustrated in figure 11. Repeated measures ANOVAs on the scales and total workload are summarized in table 13. Follow-on paired comparisons are shown in table 14. There were no significant differences across conditions on the Physical and Performance scales. On all the other scales, and on total workload, the teleoperation condition tended to have the highest workload means and the autonomous condition had the lowest means.

Table 12. NASA-TLX means.

Condition	Mental		Physical		Temporal		Performance	
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Teleoperation	14.13	8.62	1.01	2.38	10.94	7.99	8.58	4.88
Semi-autonomous	12.54	8.75	0.76	2.26	8.54	6.25	8.00	4.91
Autonomous	10.10	8.72	0.87	2.04	6.54	4.71	8.07	5.45
Condition	**Effort**		**Frustration**		**Total Workload**		—	—
	Mean	**SD**	**Mean**	**SD**	**Mean**	**SD**	—	—
Teleoperation	12.58	8.02	9.30	10.79	55.37	22.39	—	—
Semi-autonomous	8.49	7.14	7.46	9.18	45.79	19.70	—	—
Autonomous	7.29	5.97	3.93	6.13	37.82	16.81	—	—

Table 13. ANOVA summary, NASA-TLX means.

Scale	F	df	p	η^2_p
Mental	3.44	2,58	0.039[a]	0.106
Physical	<1	2,58	0.829	0.006
Temporal	4.32	2,58	0.018[a]	0.130
Performance	<1	2,58	0.858	0.005
Effort	9.14	2,58	<0.001 [a]	0.24
Frustration	4.31	2,58	0.018[a]	0.129
Total workload	9.01	2,56	<0.001[a]	0.243

[a]$p < 0.05$

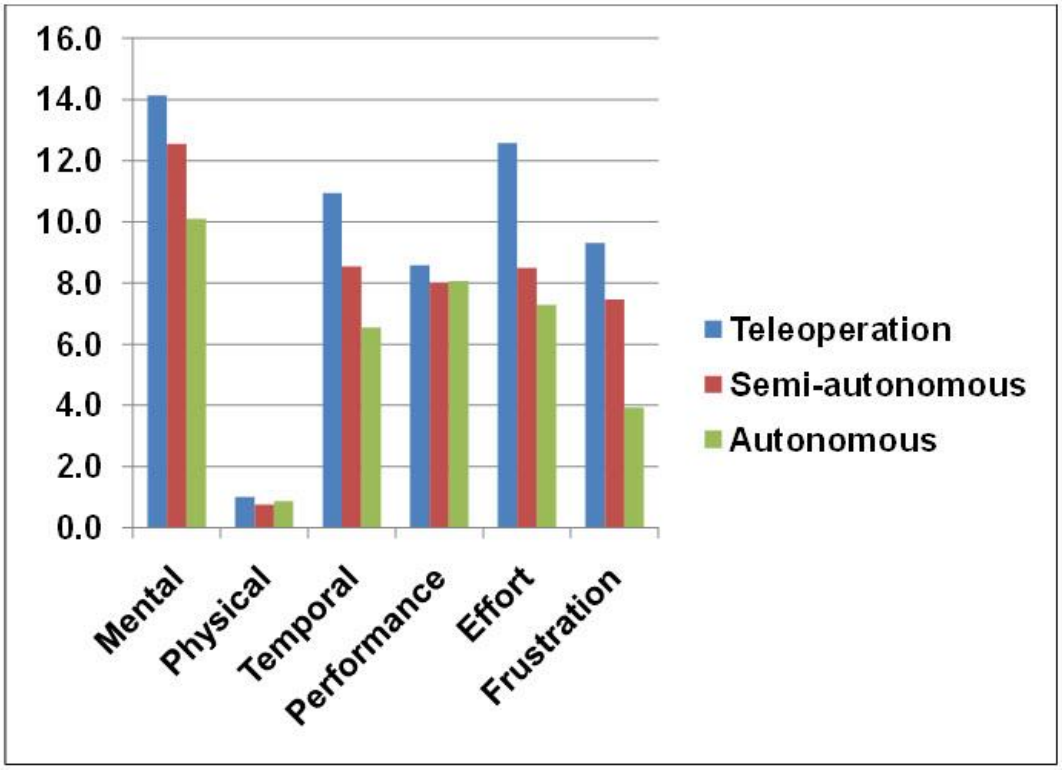

Figure 11. Mean for the three conditions on NASA-TLX.

Table 14. Follow-on paired comparisons, NASA-TLX.

Scale	Pair	*t*	df	Obtained *p*	Required *p*
Mental	Tele vs. Semi	0.93	29	0.361	0.05
	Tele vs. Auto	2.28	29	0.030	0.025
	Semi vs. Auto	2.30	29	0.029	0.0167
Temporal	Tele vs. Semi	1.47	29	0.152	0.05
	Tele vs. Auto	2.85	29	0.008[a]	0.0167
	Semi vs. Auto	1.54	29	0.135	0.025
Effort	Tele vs. Semi	3.28	29	0.003[a]	0.025
	Tele vs. Auto	3.82	29	0.001[a]	0.0167
	Semi vs. Auto	0.95	29	0.348	0.05
Frustration	Tele vs. Semi	0.98	29	0.337	0.05
	Tele vs. Auto	2.64	29	0.013[a]	0.0167
	Semi vs. Auto	2.17	29	0.038	0.025
Total Workload	Tele vs. Semi	2.10	29	0.045[a]	0.05
	Tele vs. Auto	3.67	28	0.001[a]	0.0167
	Semi vs. Auto	2.80	28	0.009[a]	0.025

[a]$p < 0.05$, 2-tailed

3.5 Questionnaire Results

Soldiers were asked to indicate their first, second, and third choice of the level of autonomy they preferred for controlling the robot while performing reconnaissance tasks. Table 15 shows the results of their ratings; the higher the mean, the greater the preference.

Table 15. Level of autonomy preferences for performing reconnaissance tasks.

	Mean Rating		
	Teleoperation	**Semiautonomous Operation**	**Autonomous Operation**
Route planning	1.62	2.04	2.35
Generating goals	1.88	1.96	2.20
Driving a straight route	1.96	2.15	1.85
Avoiding obstacles	1.81	2.04	2.15
Looking for objects of interest	2.38	1.96	1.81
Overall building reconnaissance	1.73	1.96	2.31

For the most part, the Soldiers' choices for the level of autonomy for reconnaissance tasks indicated that the more autonomy the better. Their choices for such tasks as overall building reconnaissance, avoiding obstacles, generating goals, and route planning showed their preferences for more autonomy. For driving a straight route, the Soldiers preferred semiautonomous operations because they felt that they could drive the robot faster than it traversed in the autonomous mode. They preferred less autonomy when looking for objects of interest because they could spend the amount of time they needed and go closer to the object in order to identify it.

The Soldiers were very positive about the control system because they found it to be easy to learn and to use. Many found it to be familiar because they had spent a lot of time using Xboxes. There were several complaints that the camera on the robot did not have adequate resolution and that they needed to be able to pan, tilt, and zoom the camera in order to identify objects and take pictures more easily. They also experienced some difficulty seeing the display because the room in which they were operating the robot was very bright and glare was a problem. A few Soldiers thought that a color display would assist them in identifying objects. Soldiers also complained about the latency in the system which especially impacted teleoperation.

When asked to choose if they preferred the autonomous or semi-autonomous modes, the Soldiers were closely split, with 16 preferring the autonomous and 14 preferring the semi-autonomous. Those preferring the autonomous mode did so because it freed them to do other tasks and it seemed to work smoother. Those that preferred the semi-autonomous mode did so because they could make the robot move faster and they were able to provide input. Some Soldiers did not like turning over control to the robot at all. Two of them wanted total control at all times. One Soldier commented that the use of both the semi-autonomous and autonomous modes allowed him to shift his focus to the secondary task while maintaining progress toward his primary

objective. Due to the small size of the area being reconnoitered and the number of objects in each room, Soldiers constantly had to take manual control and teleoperate the robot into position to take snapshots of the items during the autonomous and semi-autonomous trials.

Drawing an accurate map in the teleoperation condition was especially difficult. The Soldiers were extremely positive about the ability of the robot to build maps of the room and used the map frequently. Soldiers found the mapping capability in the autonomous and semi-autonomous modes particularly useful for gauging their progress while maneuvering through the building.

4. Discussion and Recommendations

Total vehicle reconnaissance times and driving errors were significantly better when the robot was in the autonomous and semi autonomous modes than when it was in the teleoperation mode. Scribner and Dahn (2008) found very little difference in driving times between teleoperation and their version of semi-autonomy called the biasing mode (the robot semi-autonomously follows a previously recorded GPS path with the operator providing course corrections for GPS path error and obstacle detection and avoidance). However, differences in the levels of autonomy of the robots in the two experiments can explain the different results. The biasing condition was different than the semi-autonomous mode of this experiment because the semi-autonomous mode included autonomous obstacle avoidance and the biasing mode required the operator to perform obstacle avoidance. The biasing mode also did not have nearly the autonomy found in the autonomous mode of this experiment. The latency (the lag between a control input and the response of the robot) complained about by the operators may also have had an impact on the results as it could have had more of a negative impact on teleoperation times and driving errors than on operation in the semi-autonomous and autonomous modes. Lane et al., (2002) indicated that system latency can actually change robotic operator control strategy from continuous command to “move and wait” which adversely impacts reconnaissance times. Over-actuation which is common when latency is unpredictable (Malcolm and Lim, 2003) can also create driving errors.

The consensus of the Soldiers was that mapping the room, driving the robot, and answering the questions in the teleoperation mode created task demands that were too difficult. On the NASA-TLX, the Soldiers rated teleoperation as creating a higher cognitive and overall work load, higher stress (frustration), more effort, and higher time pressure. While Dixon and Wickens (2003) suggested that automation would relieve cognitive overload, offloading some of the tasks by use of the autonomous modes relieved more than just the cognitive load and made the performance of the tasks much more manageable. This data is supported by Schipani (2003) who stated that workload is increased for higher levels of operator involvement. Map accuracy in the teleoperation mode was much poorer than in the autonomous and semi-autonomous modes. It was clear that the operators’ mental models of the environment, based upon viewing it through a

robotic driving camera, were fairly inaccurate. This is supported by the findings of Fong et al. (2003) who indicated that operators using teleoperation have difficulty building mental models of remote environments.

Results in the literature concerning SA and targets (objects) identified while the robot is moving are mixed concerning whether higher levels of autonomy result in better SA or vice versa. Chen and Joyner (2006) found that participants detected fewer targets when their robot was operating in the semi-autonomous mode rather than the teleoperation mode. However, automation seemed to benefit UAV pilots' target detection performance in the Dixon et al., (2003) study. Our results were different from both of the previous studies in that no significant differences were found between the levels of automation. However, if SA is more broadly defined in the Chen and Joyner (2006) study to include the gunner task and the communication task, participants did not have better SA in the teleoperation condition. The complex nature of SA and its definition makes it important to specify the definition of SA when making comparisons between studies.

5. Conclusions

Findings from this experiment indicate that as levels of autonomy increase, workload, reconnaissance times, and driving errors decrease and accuracy of mental maps increase. No differences were found in SA and target identification between levels of autonomy. Future research should be conducted to further define the areas in which automation can improve performance and decrease workload.

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Appendix A. Operations Order (Engineering Reconnaissance [FM 5-170], 1998)

This appendix appears in its original form without editorial change.

	Copy 1 of 10 copies HQ, 99th Engineer Battalion NK111111 080500 SEP 09

OPERATION ORDER 10-11

References:	1st Bde OPORD 10-23 Map sheet V107

Time Zone Used Throughout The Order: Local

Task Organization:

A/99 En Bn	B/99 En Bn 1/C/99 En Bn	Bn control C/99 En Bn (-) Recon Team 1

1. SITUATION.

a. Enemy Forces.

(1) Terrain and Weather.

(a) Observation is generally limited along the valley floor due to the terrain's undulating nature. Multiple intervisibility lines, generally running north to south and spaced between 500 to 1,000 meters, will hamper observation. Movement to the higher elevations along either the north or south wall will obviously improve observation. Winds (expected to exceed 20 knots until at least 111200 SEP 09) will lift sand from the desert floor and hamper observation. Observation at night will be extremely limited due to the light data for the next 72 hours. Note that on 8 SEP 09 the moon sets before the sun and on 9 through 11 SEP, the moon sets soon after the sun; therefore, night-vision goggles (NVGs) will provide limited capabilities for the next 72 hours and make observation, movement, and the acquisition of OBSTINTEL more difficult.

Date	BMNT	SR	SS	EENT	MR	MS	Start NVG	Stop NVG	% Illum
8 SEP	0555	0654	1701	1800	0550	1633	*****	*****	0%
9 SEP	0555	0653	1702	1801	0643	1743	*****	*****	0%
10 SEP	0555	0653	1702	1802	0731	1853	*****	*****	4%
11 SEP	0554	0653	1704	1803	0813	2002	*****	*****	9%

(b) The only cover from both direct and indirect fires is provided by the undulating terrain previously mentioned. Concealment during movement can be enhanced by traveling parallel to the intervisibility lines when available. The dusty and windy conditions may make mounted movement less detectable by the enemy.

(c) The pipeline running parallel to the LD along the 30 easting is the only existing obstacle in the AO. Crossing points for this pipeline have been identified at NK 302215 and NK 295090.

(d) The terrain in the vicinity of the templated obstacle system is believed to be unsuitable for minefield reduction by MCBs because of the undulating terrain and the soil composition.

(2) Enemy Situation.

(a) The 133d motorized rifle battalion (MRB) is currently preparing defenses along the 47 easting. This unit's expected strength is estimated to be 12 T-80s, 32 BMP-1s, 3 AT-5s, and 1 dismounted infantry company. The 133d MRB began preparing its defenses 071500 SEP and are not expected to complete its counter mobility and survivability effort before 091600 SEP. The 133d MRB is expected to have a company-size combined-arms reserve at a strength of three T-80s and eight BMP-1s.

(b) As of 080100 SEP, three enemy MRCs have been located and are depicted on the SITEMP. The expected positioning of the subordinate MRPs is also templated as well as the anticipated combat security observation post (CSOP) and artillery positions. Expect to come within direct-fire range of the CSOPs when crossing the 42 easting and the main defenses when crossing the 44 easting. Enemy artillery is expected to be in position not later than (NLT) 081600 SEP; expect to come within indirect-fire range

when crossing the 25 easting. However, the enemy will rarely use indirect fires against recon forces. Expect the enemy to use its rotary-wing assets in its attempt to try to locate and destroy recon forces. The enemy is not expected to be supported by fixed-wing aircraft. Although the enemy has the capability to employ chemical weapons, it has chosen not to do so thus far in the campaign. However, if the enemy does employ chemicals, we expect them to emplace a persistent chemical agent at center of mass NK 410280.

The enemy is not nuclear capable. Expect the enemy to use dismounted strong points to tie its obstacles into the restricted terrain at vicinities NK 450210 and NK 440100. These dismounted forces will be supplied with AT-5s to assist in their mission of preventing the obstacle system from being reduced along the walls of the valley. Additionally, the enemy will use dismounted patrols to protect all minefields.

(c) The templated obstacle system is included on the SITEMP. No confirmed obstacle locations have been obtained as of 080100 SEP. We expect the enemy to continue to lay its minefields similar to the method used throughout the campaign. We expect the enemy to mechanically lay its minefields and expect each minefield to be comprised of SB-MV mines and be 200 to 300 meters long and 60 to 120 meters deep. The mine spacing has consistently been 4.5 meters and the depths of the mines have been up to 9 inches. **NOTE: The SB-MV is magnetic-influence initiated and must be detected by probing. Operating hand-held mine detectors may detonate the mine.** If mines are surface laid, it is probably due to the soil conditions and indicates the probable success of using MCBs. The enemy has routinely used a single-strand of concertina fence on the enemy side of the minefield as a frat fence. The enemy is expected to emplace a total of 15 minefields in its defense.

b. Friendly Forces.

(1) Higher.

(a) 1st Brigade plans to conduct a brigade breaching operation and penetrate the northern MRP of the northern MRC as shown on the SITEMP. Other brigade recon assets include two COLTs and one chemical recon vehicle. The planned locations for each of these assets are shown on the maneuver graphics.

(b) Engineer recon team 1 is attempting to answer the brigade commander's PIR for location, composition, and orientation of the enemy's obstacles.

(c) If bypasses of the enemy obstacles can be located, the brigade commander would prefer to bypass the obstacles as close to the north wall as possible.

(2) Lower. Do not expect TF recon assets to cross the LD before EENT on 9 SEP 09.

2. MISSION.

The 99th Engineer Battalion conducts an area recon of NAI 301 NLT 082000 SEP 09 to facilitate the brigade's attack at 110500 SEP 09.

3. EXECUTION.

Intent. The purpose of this mission is to identify enemy obstacles within NAI 301 to confirm or deny the enemy's COA and facilitate breaching operations. The end state is the identification of enemy obstacles in NAI 301 NLT 100500 SEP 09 and recon team 1 in position at checkpoint (CP) 15 ready to link up and guide the breach force to the obstacle location NLT 110001 SEP 09.

a. Concept of Operation.

The battalion conducts an obstacle-oriented area recon. Recon team 1 will cross the LD NLT 082000 SEP. The brigade will have at least two batteries ready to provide indirect fires out to PL Celtics throughout the recon effort, and the attack helicopter battalion (AHB) will support casualty evacuation. Team 1 will cross the LD about 24 hours before the TF scouts in an attempt to observe and report the enemy emplaced obstacles and signs of recent enemy activity while the TF is still planning its R & S effort. The recon team will link up with TF 1-23 scouts (who will provide security) before conducting obstacle recon. Recon team 1 will complete its area recon of NAI 301 NLT 100500 SEP to facilitate mounted rehearsals by the brigade during daylight hours on 11 SEP 09. Recon team 1 will continue to observe NAI 301 until 101700 SEP and report any further engineer activity. At 101800 SEP 09, recon team 1 will move to CP 15 and be in position NLT 110001 SEP 09, prepared to link up and guide the breach force to the obstacle location.

b. Tasks to Subordinate Units.

(1) Battalion's TOC. The battalion's TOC will--

(a) Provide liaison personnel to co-locate with the recon team until they cross the LD and ensure that liaison personnel obtain a copy of the recon team's maneuver graphics.

(b) Coordinate the recon team's indirect fire plan with the FSO and confirm targets with the team leader once they are coordinated.

(2) Battalion S4. The battalion S4 will obtain the current logistical status of recon team 1. He will ensure that unit basic load (UBL) levels are reestablished NLT 081200 SEP 09 and report to the TOC upon completion.

(3) A/99 En Bn. A/99 En Bn will conduct liaison activities between recon team 1 and TF 1-23 according to the battalion's TACSOP.

(4) Recon team 1. Recon team 1 will--

(a) Report the current logistical status to the S4 NLT 080800 SEP 09.

(b) Backbrief the plan to the battalion commander via FM radio at 081300 SEP 09.

(c) Provide TF 1-23 the team's graphics, via the A/99 En Bn's TOC before crossing the LD.

(d) Forward requested indirect-fire targets to the battalion's TOC NLT 081600 SEP 09.

(e) Coordinate link up with the TF 1-23 scouts for security during obstacle recon.

(f) Conduct an area recon of NAI 301 NLT 082000 SEP 09 to verify the composition of obstacles within the NAI.

c. Coordinating Instructions.

(1) Task organization is effective upon receipt of this order.

(2) All units will participate in the intelligence updates to occur at 0800 and 2000 each day.

(3) The LOA for recon assets is PL Celtics.

4. SERVICE SUPPORT.

a. Support Concept.

(1) The recon team will cross the LD fully uploaded according to the battalion's TACSOP. These supplies will come from the engineer battalion. This basic load is expected to sustain the team throughout the mission.

(2) Emergency resupply will be coordinated through the engineer battalion's TOC and delivered by aviation assets. Backup resupply will be through TF 1-23.

b. Medical Evacuation and Hospitalization. The primary means of MEDEVAC is by air (requested through the battalion's TOC); backup is by ground evacuation (performed by TF 1-23).

c. Personnel Support. EPWs will be turned over to TF 1-23 for evacuation to the rear.

5. COMMAND AND SIGNAL.

a. Command. The chain of command is the commander, the XO, the S3, and the commander of C Company.

b. Signal.

(1) All traffic from recon team 1 to the battalion's TOC will be over MSRT (primary) or the battalion's command net (alternate).

(2) The recon team's current location will be sent by the battalion's TOC to TF 1-23.

(3) OBSTINTEL will be reported according to the TACSOP.

ACKNOWLEDGE:

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LTC

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Appendix B. Demographics

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SAMPLE SIZE = 30

MOS		**RANK**	**DUTY POSITION**	
09S – 10	68D – 1	E4 – 6	Air Aslt Instructor – 1	Pathfinder Instructor - 1
11B – 8	68W – 1	E5 – 17	Crew Chief – 1	Ranger Instructor – 1
11C – 1	88M – 2	E6 – 2	Driver – 1	Support – 1
12B – 1	0CS – 3	OCS – 4	Instructor – 1	Team leader – 4
15T – 1	NR – 1	NR – 1	Medic – 1	Training – 1
31B – 1			OCS – 7	NR - 9
			Combat Engr - 1	

AGE

28 years (range 21-47)

1. How long have you served in the military? 65 months (mean)

2. How long have you had an infantry-related job? 72 months (mean)

3. How long have you been a fire team leader? 21 months (mean)

4. How long have you been a squad leader? 44 months (mean)

5. How long have you been deployed overseas? 21 months (mean)

6. How long have you been deployed in a combat area? 15 months (mean)

7. With which hand do you most often write? 25 Right 5 Left

8. With which hand do you most often fire a weapon? 27 Right 3 Left

9. Do you wear prescription lenses? 4 Yes 26 No

10. If yes, which do you wear most often? 2 Glasses 2 Contacts

11. Which is your dominant eye? 26 Right 4 Left

12. Do you have any vision related problem? 2 Yes 27 No 1 NR
If so, what? Red/green color blind (1), farsighted (1)

13. Have you ever used a robotic system? 1 Yes 23 No 6 NR
If so, what type? Davinci (1)

14. Please describe the conditions under which you used the robotic system.
Surgical (1)

15. Using the scale below, please rate your skill level for each of the following activities.

None	Beginner	Intermediate	Expert
1	2	3	4

ACTIVITY	MEAN RESPONSE
Operating ground unmanned vehicles	1.13
Operating aerial vehicles	1.09
Target detection and identification	1.55
Playing commercial video games	2.65
Training with Army video simulations	2.17

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Appendix C. Training Questionnaire

This appendix appears in its original form without editorial change.

SAMPLE SIZE = 30

1. Using the scale below, please rate the training you received in the following areas.

1	2	3	4	5	6	7
Extremely bad	Very bad	Bad	Neutral	Good	Very good	Extremely good

	MEAN RESPONSE
a. Introductory robotic training	
--Completeness of introductory training	5.90
--Comprehension of the overall concept of the robot	5.90
b. Building reconnaissance training	
(1) Robotic driving	
--How to drive the robot (teleoperation)	5.73
--How to drive the robot (semiautonomous)	5.70
--How to drive the robot (autonomous)	5.97
(2) Time provided to practice driving the robot on the building reconnaissance course	
--Teleoperation	5.59
--Semiautonomous	5.55
--Autonomous	5.81
(3) How to complete the building reconnaissance course (independent of levels of autonomy)	
c. Overall evaluation of the robotic training courses	5.96

Comments	**No. of Responses**
I personally was challenged; not a video gamer.	1
Instructions were great!	1
b. Building Reconnaissance Training	
I liked the tele mode best.	1
More time makes you better, but for what we did today, it was enough.	1
The auto was the easiest level because it gives you the opportunity to multitask a lot easier than the other two settings.	1
More distractions perhaps.	1
Attempting to draw to scale, take pictures, and maintain awareness may be a problem in the tactical field.	1
Drawing/mapping was difficult.	1
c. Overall Robotic Training	
Extremely fun and helpful for the future of operation.	1
Great ideas, tech, instruction.	1
d. Speech Training	
Would free up more time and frustration.	1
Need a little more time with it. I felt like I had more time with grenades and the robot besides the speech control.	1
Not good at all in my case, but that has to do with my ability in speaking English.	1

2. What were the easiest and hardest training tasks to learn?

Comments	**No. of Responses**
Easiest	
All of them.	1
Training on all was performed well.	1
The task of each control.	1
Control of robot (driving, steering, moving, maneuvering, etc.).	12
Use of controller.	1
Using controls to draw the map.	1
Learning how the remote control works, and what buttons do what.	2
Taking pictures.	8
Collect intel.	2
Photographing and identification.	1
Identify weapons and other items.	1
Labeling pictures.	3
Identifying obstacles.	1
Autonomous was the easiest.	2
Tele and Semi were the easiest.	1
Hardest	
None of them, at least to me.	1
Doing the entire job. Better to just be in the room.	1
Feeling the turn radius of robot.	1
Getting robot to move easier. They should find a way to have pivot points instead of tracks so the robot eye is multidirectional and independent of the mobility of the robot itself.	1
Robot has difficulty with full autonomous mode in close areas.	1
Prioritizing the video with the map for situational awareness.	1
How to work my way through the building. I didn't like the delay using the map in relation to my controls was unclear.	1
Mapping the building by hand.	4
Drawing the map during building reconnaissance.	1
Answering questions while driving robot.	3
Situational awareness.	1
Object identification.	1
Driving around obstacles.	1
Speech training/controls.	2
Taking pictures. But once you get used to it, it becomes very easy.	1
Labeling the pictures.	1
Overall functions of each button.	2
Using the joystick/control pads.	1
Understanding that you have "tunnel vision" with the robot.	1
Tele was the hardest.	2
Autonomous was the hardest.	1

3. What are your overall comments on the training?

Auto and Semi worked great.	1
Good.	7
Good learning experience; something I've never seen before.	2
Fantastic tool. Can see how this will save more lives by using the robot as the recon tool.	1
Interesting and fun.	3
Easily understood what to do during these exercise.	1
Fairly simple.	1
Cadre was very informative.	1
I'm glad I got to participate.	1
Would like to see how it works with a two-man team with the same evaluation.	1
I feel everyone was very knowledgeable and professional.	1
Full instructions; good review.	1
I felt very comfortable operating the robot.	1
Could use on battlefield in urban areas.	1
I would like to do it in a real mission.	1
Could use more time to practice controlling robot.	1
Driving the robot and not running into everything, like the edge of a door.	1
Display hard to see.	1
The use of the directional pad would have been great to have known about in the training so I could practice.	1
The tele operation and map drawing was extremely difficult to do both under a set time.	1

Appendix D. Post Iteration Questionnaire

This appendix appears in its original form without editorial change.

SAMPLE SIZE = 30

AUTONOMY LEVEL:
TELEOPERATION (TELE), SEMIAUTONOMOUS (SEMI), AUTONOMOUS (AUTO)

1. Using the scale below, please rate your ability to perform each of the following **tasks** based on your experience with the autonomy level that you just used.

1	2	3	4	5	6	7
Extremely difficult	Very Difficult	Difficult	Neutral	Easy	Very easy	Extremely easy

	MEAN RESPONSE		
	TELE	**SEMI**	**AUTO**
a. Move the robot in the correct direction	5.23	5.20	6.00
b. Avoid obstacles	5.14	5.50	5.48
c. Avoid pot holes	5.67	5.50	7.00
d. Assess down slopes for navigatability	5.50	5.67	7.00
e. Assess side slopes for navigatability	5.50	5.67	7.00
f. Identify any other terrain features that might have an adverse effect on the ability of the robot to maneuver through the terrain	6.13	6.38	6.00
g. Anticipate whether the ground clearance of the vehicle will allow negotiation of rugged terrain	6.25	6.80	6.67
h. Anticipate whether the turn radius of the vehicle will allow a turn	4.67	4.65	5.32
i. Identify if the robot is on the correct path	5.38	5.37	5.72
j. Navigate far enough ahead to plan route in advance	5.14	5.21	5.27
k. Navigate well enough to drive at slowest speeds	6.00	6.17	6.22
l. Navigate well enough to drive at medium speeds	5.75	6.00	6.05
m. Navigate well enough to drive at fastest speeds	5.32	5.38	5.74
n. Finish the course quickly	4.07	4.75	5.34
o. Ability to find IEDs and other objects of interest	5.69	5.86	6.00
p. Ability to navigate to the next waypoint	5.50	5.68	5.72
q. Ability to map the room (building reconnaissance course only)	3.75	6.00	6.21
r. Ability to take pictures	6.40	6.29	6.37
s. Ability to make the robot understand you	5.88	5.21	5.65
t. Ability to maintain situation awareness	4.37	4.97	5.38
u. Overall ability to perform this reconnaissance with this level of autonomy	4.35	5.20	5.86

Comments	No. of Responses
TELE	
Mapping room accurately was difficult.	1
If the camera on the robot could zoom in and out, it would help out a lot.	1
Camera does not allow any view other than forward at ground level. Can't tell how close it is to objects. Can't see anything that could be happening behind robot, i.e., rear camera.	1
This mode is difficult as one person. If a two-man team was involved, it would be easier by a lot.	1
SEMI	
Seems the easiest and most effective.	1
Good, because you can let the robot move on its own and stop it and take control if you wanted to.	1
Performing functions on the controller became easy to remember after a few repetitions; approx 10 minutes.	1
The directional pad wouldn't respond well (slow or not at all). The robot moves extremely slow and "thinks" too much for each breach of a room. It was faster to just let it go into a room and then take control.	1
The joystick sensitivity is not high enough.	1
In my opinion, this level is worthless because I had to operate it more than by itself.	1
I prefer the autonomous more.	1
AUTO	
It was easy for me to answer questions and look up info in this mode.	1
Easier with practice.	1
Overall felt like the same as semi. Seemed more efficient to continually take over rather than allow robot to maneuver on its own the whole time due to number of items.	1
Unable to label some objects due to low camera resolution or perhaps light levels.	1

2. Please check any of the following conditions that you may have experienced during this trial.

	NUMBER OF RESPONSES		
	TELE	SEMI	AUTO
Eyestrain	7	7	4
Tunnel vision	2	2	1
Headaches	0	1	0
Motion sickness	0	0	0
Nausea	0	0	0
Disorientation	2	0	0
Dizziness	0	0	0

Competition between eyes for vision of different scenes at which they are looking	2	3	1
Any other problems?	0	1	0

Comments	**No. of Responses**
BUILDING RECONNAISSANCE	
TELE	
Competition between eyes when trying to look at the screen and draw at the same time on your map. If I were the operator, I would have an assistant to map it.	1
Eyestrain from glare on the computer screen.	1
Screen should be bigger or be in room with less light.	1
SEMI	
Some items were a little hard to make out with the camera and caused eyestrain.	1
AUTO	
Training is easy.	1
Some items were a little hard to make out with the camera and caused eyestrain.	1
I would be able to ID smaller objectives if there was a zoom feature on the camera.	1
Possible color vision.	1
Larger screens, even for training purpose.	1

3. Using the scale below, what is your **overall rating** of the level of autonomy you used on this course.

1	2	3	4	5	6	7
Extremely bad	Very bad	Bad	Neutral	Good	Very good	Extremely good

MEAN RESPONSE		
TELE	**SEMI**	**AUTO**
4.63	5.11	5.63

Comments	**No. of Responses**
BUILDING RECONNAISSANCE	
TELE	
Useful and probably more practical; however, it is difficult to do as one person.	1
I prefer the control of the robot, but ability to map was difficult.	1
Having to drive, map, and answer questions was too much.	1

Comments	No. of Responses
When in full tele mode, it is hard to concentrate on main mission while having to react to outside influences. With this, frustration comes in making tasks seem even more difficult.	1
The controls are hard to turn.	1
Fixed camera may be a problem.	1
Rear camera would be nice as well.	1
Robot if tactically possible could sit higher from ground level or the camera.	1
SEMI	
Allowed focus to be shifted to the secondary objective while maintaining the primary objective.	1
Like playing with a toy/Xbox.	1
I had a tendency to want to have more control over the robot.	1
Rough control over the robot.	1
I didn’t like it at all. I’d rather use Tele where I am in total control. But, of course, I believe that would be subject to change if I had more practice with it.	1
Robot overlooked nearly an entire room, and got itself stuck against a wall. Definitely had to navigate some with remote; very simple.	1
This level is worthless to me and the camera could be better with clarity and the ability to zoom in and out.	1
Not as aware of surroundings.	1
AUTO	
Robot did its job very well allowing me to add focus to secondary objectives without compromising my primary goal.	1
This mode makes it easier than the other two. It allows you to multitask a lot easier than the other two.	1
Autonomous mode seems to be the way to go.	1
Very good. Can I come back and do this tomorrow?	1
I think the camera should be providing a better resolution and should be moveable.	1

INTENTIONALLY LEFT BLANK.

Appendix E. End Of Experiment Questionnaire

This appendix appears in its original form without editorial change.

SAMPLE SIZE = 30

1. Using the scale below, please rate the following characteristics of the control system that you used.

1	2	3	4	5	6	7
Extremely bad	Very bad	Bad	Neutral	Good	Very good	Extremely good

CHARACTERISTICS	MEAN RESPONSE
a. Resolution (clarity) of the display	4.63
b. Size of objects appearing in the display	4.90
c. Ability to adjust display	3.83
d. Comfort of viewing the display	4.30
e. Display brightness	4.77
f. Effect of glare on the display	4.03
g. Contrast between objects on the driving display	4.93
h. Display color	4.13
i. Comfort of using the display	4.73
j. Number of controls	5.23
k. Control locations	5.43
l. Size of individual controls	5.67
m. Complexity of controls	5.40
n. Ability to use controls without inadvertently activating other controls	5.60
o. Size of entire control unit	5.80
p. Adequacy of this control unit for teleoperating a robot	5.60
q. Adequacy of this control unit for semi-autonomously operating a robot	5.67
r. Adequacy of this control unit for autonomously operating a robot	5.87
s. Overall assessment of this control unit	5.40

Comments	**No. of Responses**
The map display overhead was excellent. The robot updated the mapping of the room fast and accurately.	1
I liked the familiarity of the Xbox controller.	1
Display was small and lack of optics.	1
The most difficult part was identifying objects being displayed by the camera.	1
Picture quality wasn’t too good. Couldn’t tell what some items were.	1
Depth perception on display was hard to determine.	1
The lack of clarity and color sometimes caused me to see a splotch on the low part of a wall or floor and think it was an object.	1
The display would be better if it was in color. It would be easier to ID clothing, bloody rags, etc.	1

Comments	No. of Responses
Had trouble reading maps/writing on the wall.	1
More time to practice would have played a bigger part in rating this unit higher.	1

2. Please indicate your 1st, 2nd and 3rd choice of the level of autonomy to use for completing the following tasks by placing a 1, 2, or 3 in the appropriate column.

	MEAN RATING		
	Tele-operation	**Semiautonomous operation**	**Autonomous operation**
Route planning	1.62	2.04	2.35
Generating goals	1.88	1.96	2.20
Driving a straight route	1.96	2.15	1.85
Avoiding obstacles	1.81	2.04	2.15
Looking for objects of interest	2.38	1.96	1.81
Overall building reconnaissance	1.73	1.96	2.31

3. What suggestions do you have for ways to increase the effectiveness of the following modes?

Comments	No. of Responses
Teleoperation	
I liked tele because I was in control; but I wasn't a fan of the mapping.	1
Tele mode offers more freedom and choice when operating the robot, but it takes too much time.	1
Easy to operate but you have to do everything manual so it is a little more time consuming.	1
Side/rear cameras.	1
Robot still has the ability to map.	1
Symbols on control pad to show what it will do (photos).	1
Improve lag.	3
Adjust screen so that visibility is clearer.	1
Wide angle screen.	1
Being able to use the laser rangefinder.	1
Better zoom on camera.	1
Better camera clarity and angle of view.	1
Hot keys to quickly mark/label items of interest.	1
Color monitor.	1
Fewer distractions.	1
Automatically go to label a picture after one is taken.	1
The controls for picture taking and being able to label were confusing	1

Comments	No. of Responses
after a while.	
Better nav controls.	1
Improve signal for response.	2
Less questions.	1
Semiautonomous	
Works well.	1
More responsive to user suggestions while driving.	1
Responsiveness could be slow, from switching in and out of semi mode. Got stuck at one point.	1
Make more like autonomous where it will scan the room while moving.	1
Robot identifies objects that are inconsistent with surroundings more clearly.	1
Use to ID objects.	1
Lower speed to stop for pictures.	1
Improve lag.	2
Better zoom on camera.	1
Hot keys to quickly mark/label items of interest.	1
Get rid of it because you spend more time in the tele mod.	1
Color monitor.	1
Wide angle screen.	1
Did not like because it was like a retard robot.	1
Symbols on control pad to show what it will do (photos).	1
Could have a temp pause button instead of two (one to stop and one to resume).	1
Autonomous	
This is the best mode.	1
Worked great!	1
Excellent for the job and really simple.	1
Works well.	1
Speedy.	1
Full room scans via camera.	1
Color monitor.	1
Wide angle screen.	1
Better zoom on camera.	1
Hot keys to quickly mark/label items of interest.	1
Screen clarity.	1
Make sure the robot travels to every corner of the room so the operator can see everything before it moves on to the next room.	1
Limits the effectiveness of how well you can conduct recon on a building.	1
Symbols on control pad to show what it will do (photos).	1
Help robot navigate around objects easier.	1
Time delay.	1
More practice on it.	1

4. Using the scale below, please rate the level of reliability (trust) of the autonomous systems you used.

1	2	3	4	5	6	7
Extremely unreliable	Very unreliable	Unreliable	Neutral	Reliable	Very reliable	Extremely reliable

	MEAN RESPONSE
Semi-autonomous	5.43
Autonomous	5.68

No comments.

5. Using the scale below, please rate how helpful the following capabilities were to your ability to drive/control the robot in the semi-autonomous and autonomous modes.

1	2	3	4	5	6	7
Extremely unhelpful	very unhelpful	unhelpful	neutral	helpful	very helpful	extremely helpful

CAPABILITY	MEAN RESPONSE
a. Robot's position/location	5.57
b. Showing the path the robot drove	5.80
c. Obstacle avoidance	5.53
d. Ability to return to "start location"	6.27
e. Map data (robot built)	6.11
f. Capability of the robot to drive itself	6.00

6. Would you want the following capabilities again if you have to perform these same missions over again?

	NUMBER OF RESPONSES		
	YES	NO	NR
a. Robot's position/location	25	1	4
b. Showing the path the robot drove	25	1	4
c. Obstacle avoidance	26	0	4
d. Ability to return to "start location"	25	1	4
e. Map data (robot built)	24	0	6
f. Capability of the robot to drive itself	26	0	4

7. How would you improve the robot and/or any of its features?

Comments	**No. of Responses**
Better camera with higher resolution.	7
Improve clarity or provide light source of some kind.	2
Bigger camera view.	3
Camera positioning and control.	1
Moveable camera with zoom feature.	2
Add a wider lens that elevates and swivels for easier identification.	1
An arm and elevation on camera.	1
Add a scanning laser that identifies objects as question marks on the screen in the auto mode.	1
Constant stopping and adjusting view in the tele mode for pictures took lots of time. Maybe add in a “room scan” so the robot automatically visually covers whole room.	1
Photos can be pop-up windows (1-10), then you can label from there instead of having a picture in the middle of your pathway on the display.	1
Adjust photo movement (up and down).	1
If the robot would recognize and take photos on its own.	1
Add an extension for the lens.	1
Lag time was main problem and it got confused sometimes concerning where it was going; maybe make an adjustment for that.	1
Avoiding obstacles a little better in semi and auto modes.	1
The avoidance feature needs to be able to be deactivated.	1
Map data needs to be clearer.	1
Improve the elevation view and the capability to climb stairs and not get stuck.	1
Height of robot.	1
Speed.	1
Turning ability.	1
Make it lighter so it would be easier to transport and add a light to illuminate objects that are in the dark.	1
Quieter.	1

8. How would you improve the interface and/or controller?

Comments	**No. of Responses**
Already good.	2
Very easy to understand; leave as is.	5
Most soldiers are into games, so that type of controller works in this situation.	1
Perfect controller.	2
Different control.	1
Add hot keys to quickly mark/tag items of interest.	1

Comments	No. of Responses
Add a button for elevation scan.	1
Add a warning LED when in tele to warn the user of objects that they will hit.	1
Add an instrument panel that shows distance cleared, total distance traveled, height of the room, etc.	1
Improve lag on display.	1
Identify objects on map more clearly.	1
Video display should take up about half of the screen. When a lot of objects were nearby, it was difficult to tell one picture from another. The labels should be in alphabetical order when they are displayed.	1
Faster mouse speed.	1
Asking for a label automatically whenever a picture is taken.	2
The X,Y,A,B buttons would be better for selecting items, taking pictures, zoom in and out. These are the closest buttons to your hand and the most used. The LB and RB are the least used in Xbox games for that reason. They are inconveniently placed and awkward.	1
Alternate controls (dual-stick tank control).	1
It is easier to view with right thumb stick left/right and move with the left thumb stick.	1
Perhaps 360^o viewing ability.	2
Get more input from gamer for functionality.	1
Bigger joystick with movement buttons on it instead of controller front.	1
Larger screen for room/path image.	1
Wide angle lens.	1
Color.	1
Zoom feature on the video screen bottom; sort of like a drop-down menu when you change the size of your pictures on your PC when you print.	1

9. a. Did you feel a difference between the semi-autonomous and autonomous modes?

_9_ No
_21_ Yes

b. If yes, what was the difference(s)?

Comments	No. of Responses
Auto	
The auto mode will go into a room and scan the room for you giving you more time to look for things.	1
Lets you go from A to B and work backwards from B to A.	1
Seems to return to the starting position more quickly and efficiently.	1
Ease of operation and speed.	2
More aware.	1
Maps better.	2

Comments	No. of Responses
Easier to focus on what to take photos of, instead of doing both.	1
Total tech control.	1
Recons the site faster.	1
Semi	
Semi mode moved distances faster.	1
The robot moving itself.	1
Ease of movement in between objects.	1
Semi seemed to be smoother with the controls.	1
More control (without stopping).	3
Obstacle avoidance and new unidentified exploring.	1
User input during semi mode was helpful.	1
You pay attention to making corrections and having to over compensate.	1
Messed up (got stuck, lagged – not a fan!).	1
Does not seem as aware as auto.	1
General	
The difference was hard to discern because I was stopping the robot just as often in both to take pictures.	

10. a. Which mode do you prefer?

  16 Autonomous
  14 Semi-autonomous

b. What are the reasons for your preference?

Comments	No. of Responses
Autonomous	
Didn't lag, ran smoother. I never got stuck. Felt like I could look at OPORDER and not worry if it'd get stuck or confused.	1
Easier to work with because it goes to every corner of the building.	1
Easy to operate and I like to see the area with everything in it.	1
More comprehensive and fully maps building.	1
Ability to focus more on the screen than controlling.	1
Allows me to concentrate on objects that can make/break the mission success.	1
Ease of operation and speed.	1
Lets you multitask easier.	3
Seemed to know where it was going.	1
I don't really get the difference between the two. I understand what it's supposed to do, but mostly I just stopped it and ran it on my own.	1
Semi-autonomous	
Ability to guide robot during travel.	1
It still seemed necessary due to the number of items and also the robot started to skip past a room. Although it may have eventually gone	1

Comments	No. of Responses
back, it seemed more efficient to just take control.	
Semi is faster at distance travel.	1
I like the interactive control.	1
I feel I have more and faster control of the robot.	5
Moving on its own and still having control.	1
Easy to change course slightly.	1
Best feature is the robot driving itself. Therefore, they were both a good feature.	1
Exploring something quickly and laying out the floor plans.	1
Manual control is preferred.	1

11. In the semi-autonomous and fully-autonomous modes, the robot automatically built a floor plan of the building for you. How often did you use the floor plan as you looked for objects of interest? How was it helpful or not helpful?

Comments	No. of Responses
Very often. Absolutely helpful.	7
It helped me know where I was at all times.	1
I constantly viewed the mapped floor plan to know where the robot had gone and where it needed to go.	1
Allowed for easy positioning, along with mission check.	1
Map reading and using a map may seem out of date; however, it is of great importance to the Infantry.	1
Probably the most important tool. I used it to see where the robot had been and what pictures I'd taken, areas I needed to search, and the route I took. It was a very good and important asset to the operation.	1
I used the floor plan just to see the parameters of the building and to see where the robot was in the building initially. But I could have figured these things out myself. However, the floor plan was helpful because it was an added visual that showed where the robot had been in the building during the recon.	1
80 percent of the time. Allowed you to scan for items or interest.	1
Used it often to find out where I was and where I needed to look.	2
Used often to check for missed doors.	1
It was helpful, but didn't use it very much.	1
It helped more with the basic area to work in.	1
You knew where you have already been as far as room clearing. It was helpful in that manner.	2
Good for reference to whether photographed object yet or not.	1
I used it to make sure I didn't miss anything and rooms. When I was in full control, I worked the rooms clockwise making sure it was completely cleared before moving on, and then continued. When done, I went straight back to the beginning by pressing the return home	1

Comments	No. of Responses
button.	
I didn’t really use it other than to tell if I had already been in that room. Semi-helpful.	1
Somewhat helpful. The area being explored was small, so the mapping feature was less important. However, in a large building the mapping feature would be extremely useful.	1
It was helpful until it started wandering aimlessly without completing the course. The floor plan confused me.	1
It was helpful but not fresh in the room. Maybe to have an understanding for other sources or reasons. For example, the robot takes pictures and has a floor plan. Now another group can come in to collect intel knowing already what’s there getting themselves in it.	1
Not very helpful at first, but as I got more comfortable, the usefulness increased.	1
Sometimes I spent more time looking at/for objects and determining what they were.	1
I did not use it much to find objects; however, the map is incredibly useful for site recon and future operations. It gives a much more accurate assessment than I could draw using the display.	1
I only used the floor plan to go back and make sure I didn’t miss any hidden items.	1

List of Symbols, Abbreviations, and Acronyms

ACS	Autonomous Capability Suite
ANOVA	analysis of variance
ARL	U.S. Army Research Laboratory
COTS	commercial grade off-the-shelf
GPS	global positioning systems
HRED	Human Research and Engineering Directorate
IMU	inertial measurement unit
MOCU	Multi-Robot Operator Control Unit
MOUT	military operations in urban terrain
NASA-TLX	National Aeronautics and Space Administration-Task Load Index
OCS	Officer Candidate School
POW	prisoner of war
SA	situation awareness
SSC Pacific	Space and Naval Warfare Systems Center San Diego
SUGV	small unmanned ground vehicle
WTC	Warrior Training Center

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